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(54) IMPROVEMENTS IN OR RELATING TO X-RAY TUBES

(71) RIGAKU DENKI COMPANY LIMITED, a Japanese Company of No. 9-8, Sotokanda 2-Chome, Chiyoda-Ku, Tokyo Japan, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

The present invention relates to X-ray tubes and in particular relates to a cooling system for thin target X-ray tube devices.

In various X-ray measurement or observation apparatus including X-ray microscopes and X-ray diffraction apparatus, and particularly in research on X-ray diffraction figures by the Kossel pattern technique or in microscopic photographs of X-ray figures, an X-ray tube having a focal point sufficiently small in size and capable of generating a strong X-ray is required. In such an X-ray tube, a minute focal point of an electron ray having a size of, for example, several-tens of microns is formed on a thin metal target having a thickness of, for example, several tens of microns.

In such an X-ray tube, the focal point area on the thin target is locally heated to a high temperature and consequently is fused. Therefore, an electron current higher than about 100 μA cannot pass even when the back surface of a thin target is cooled directly by flowing cooling water thereover, the cooling water boils at the back side of the focal point on the back surface of the target, resulting in formation and build-up of "fur".

The invention seeks to provide means for effectively cooling a thin target for an X-ray tube.

The invention seeks also to provide a water cooling system for cooling a thin target of an X-ray tube, which system is simple in construction but efficient in operation.

Furthermore the invention seeks to provide an X-ray tube which is capable of generating strong X-rays through a minute focal point formed on a thin foil-like target.

Yet again the invention seeks to provide an X-ray tube which is arranged to prevent a minute focal point on a thin foil-like target from oxidation due to heating.

According to the present invention an X-ray tube comprises an electron gun disposed adjacent one end of an elongate electron beam focussing tube, a thin target disposed at the other end of the tube and arranged to be bombarded by the accelerated electron beam, and protective means associated with the target to enhance the ability thereof to withstand deterioration which would result from bombardment by said beam, including target supporting means, said target extending across the convergent-end of a conical opening in said supporting means so that a portion of the target is exposed at said opening, and a cooling block having a channel for the passage of a cooling fluid therethrough at least at the side of said target remote from the beam and arranged so that said side of the target has a surface area surrounding the exposed portion which is in mutual thermal exchange contact with a cooling surface or surfaces, said thermal exchange contact-area extending over a major part of the cross section of said end of the tube major part means at least 50% of the cross-sectional area.

A preferred example is one wherein the whole of the area of said one side of the target surrounding the exposed portion is in thermal exchange contact with a cooling surface consisting either of the block or partly of the block and partly of the cooling fluid.

The invention will be described further, by way of example, with reference to the accompanying drawings, in which:—

Figure 1 shows a section of a preferred embodiment of the present invention,

Figure 2 shows a section of a preferred embodiment of the target of the X-ray tube,

Figure 3 shows a section taken along line III—III in Figure 2,

Figure 4 shows a section of a second preferred embodiment of the present invention,

Figure 5 shows a section taken along line V—V in Figure 4,

Figure 6 shows a section of another modified form of the X-ray tube of the present invention,

Figure 7 shows a section in an enlarged scale of the target portion of Figure 6,

Figure 8 shows a section taken along line VIII—VIII in Figure 7,

Figure 9 is a schematic drawing to illustrate the principle of the present invention, and

Figure 10 is a diagram showing a heat radiation curve used to describe the present invention.

Referring to Figure 1, an elongate metal tube 1 is provided at one end thereof with an electron gun including a Wehnelt electrode 2 and a filament 3. A negative high voltage is applied to the electrode 2 and the filament 3, and an electron current focussing coil 4 is fitted over the tube 1 to surround the tube. The other end of the tube 1 is provided with a pair of cooling blocks 5, 6 having a cooling water channel and a target foil.

More particularly, the said other end of the tube 1 is provided with a suitable target foil 7 of a metal such as copper, aluminium or gold interposed between a pair of discs 5 and 6 fitted into the tube 1. The target foil 7 has a thickness within the range from several tens of microns to several hundred microns. The discs are formed with coaxial conical central openings 8 and 9 respectively, the diameter 2R of the openings at their contiguous apexes being formed so as to provide a desired diameter of a focal point. A pair of similar annular cooling water passages 10, 11 are formed in the discs 5, 6 respectively adjacent the apexes of the conical openings 8, 9. The passages 10, 11 in the respective discs 5, 6 together form a toroidal cooling channel coaxial with the conical openings 8, 9 and equatorially divided by the foil 7 into equal and opposite channels. The passages 10, 11 respectively merge into radial extensions, which, at the edges of the discs 5, 6, are connected to an inlet pipe and an outlet pipe respectively coupled to the elongate tube 1.

In the X-ray tube arranged as described above, the electron current discharged from the filament 3 is intensified by the elongate tube 1 to a voltage of several tens of thousand volts and when the resultant electron current beam *e* is focused to the apex of the conical opening 9 by the coil 4, a portion of the focused current beam hits the portion of the target foil 7 exposed at the apex of conical opening 9. Since the foil is very thin, a portion of X-rays generated by the electron beam bombardment passes through the foil and is emitted through the opposite opening 8 to the outside as indicated by arrows *x*. Thus, the electron beam *e* hits a relatively large area of the inner surface of the conical opening 9, but the portion permitted to pass through the opening 9, foil 7 and opening 8 so as to become the source of X-rays, is defined by the diameter 2R at the apexes of the openings. This is, for example, several tens of microns.

Although electron beams *e* hit a relatively large inner surface area of the conical opening 9 and the portion of the foil 7 exposed to the opening at the apex, there is no danger of excessive local elevation of the temperature at the portions bombarded by electron beams since the opening 9 is formed in the disc 6 which has a sufficient thickness and is formed of a metal having a good thermal conductivity, for example, not less than that of steel. The foil 7 is bombarded and thus heated by electron beams only at its exposed portion. Since the area of the target surrounding the exposed portion is in thermal exchange contact directly with the discs 5, 6 formed of a good heat conductive material and having the cooling water passages 10, 11 respectively arranged adjacent said portion, the vicinity of the exposed portion of the foil 7 is maintained at a temperature substantially equal to that of the cooling water. Now, assuming that the thickness of the foil 7 is *s* and that the calorific effect, expressed as the number Q of heat units generated by the electron beam, is distributed uniformly in the foil, and the density of the electron beams is also uniform, then for simplifying the analysis, the calories Q1 generated within a circle with a radius *r* from the centre of the exposed portion of the foil 7 may be expressed as follows:

$$Q_1 = \frac{\pi r^2}{\pi R^2} Q = \left(\frac{r}{R}\right)^2 Q \qquad (1)$$

Where the temperature gradient at radius *r* is dt/dr and the thermal conductivity of foil 7 is *k* the number of calories Q_2 absorbed by a circular cross section of the coil 7 with radius *r* is:

$$Q_2 = k.\ 2\pi rs \frac{dt}{dr} \qquad (2)$$

If the scattering of heat due to radiation and convection is ignored, the generated heat Q_1 and the absorbent heat Q_2 are equal in normal condition,

$$\left(\frac{r}{R}\right)^2 Q = 2\pi krs \frac{dt}{dr} \qquad (3)$$

thus,

$$\frac{dt}{dr} = \frac{Q}{2\pi ksR^2} r \qquad (4)$$

Therefore, the temperature difference T between the centre of the exposed foil portion and its periphery is:

$$T=\frac{Q}{2\pi ksR^2}\int_0^R rdr = \frac{Q}{4\pi ks} \quad (5)$$

Hence, if the temperature of cooling water is T_1, the temperature at the centre of the exposed portion of the foil 7 may be obtained in the following manner:

$$To=T_1+T=T_1+\frac{Q}{4\pi ks} \quad (6)$$

Thus the temperature at the centre of the exposed foil portion where it is heated most intensively is not dependent upon the radius R of the exposed portion.

If the acceleration potential of the electron beam is constant, the total number of calories generated by the beam at the exposed portion of the foil will depend upon the value of the electron current hitting the portion. Therefore, if the highest permissible temperature without melting or damaging the foil 7 is constant, the exposed foil portion, regardless of its radius R, may be bombarded with constant electron beams whereby X-rays may be generated. In other words, with the smaller X-ray focal point provided by forming smaller apexes of the conical openings 8, 9, the electron beam density is made greater, whereby the magnitude of the electron current hitting the exposed portion of the foil 7 may be always maintained at a constant value. In this manner, X-rays of a substantially constant intensity may be provided regardless of the size of the X-ray focal point. Thus, an X-ray tube having an extremely small focal point and capable of generating strong X-rays may be provided.

Since the X-ray generating portion of the X-ray tube is directly cooled by water, the cooling at the portion may be carried out very effectively and efficiently. Furthermore, X-rays of a constant intensity may always be provided regardless of the size of the focal point, and since the cooling efficiency is high, the electron beam accelerating potential may be increased. In such a case, the electron beam penetrates deeper into the foil to generate X-rays at deeper portions of the foil, thus to emit stronger X-rays from the back surface of the foil. It is a further advantage of the present invention that with the smaller focal point, the force on the back of the foil due to atmospheric pressure is lower, and therefore, a thinner foil may be used, whereby stronger X-rays may be obtained.

In the second embodiment shown in Figures 4 and 5, the disc 6 as shown in Figure 2 and 3 is omitted while an X-ray window 12 is formed through the wall of the tube 1 and the window 12 is closed and hermetically sealed with a beryllium cover plate 13. In this embodiment, a laminar electron beam (e) bombards the apex of the opening 8. The manner of emitting X-rays x1 from the back surface of the foil 7 through the opening 8 is similar to that of the embodiment shown and described with reference to Figures 2 and 3. In this embodiment, however, when the window 12 is so positioned as to face the side of a wide electron flux (e), X-rays (x_2) emitted from the surface of the foil 7 through the window 12 and the beryllium cover plate 13 form a linear focal point as shown; and when the window is positioned to face the side of a narrow electron flux, X-rays (x_2) form a spot focal point effectively. The X-ray tube of this form is of a multipurpose type, i.e. X-ray microscopic photographs may be taken by utilising X-rays emitted from the opening 8, while, for example, the observation of X-ray diffraction may be carried out using X-rays emitted through the window 12.

The third embodiment is shown in Figures 6 through 10. In this embodiment, the elongate metal tube 1 which is similar to that shown in Figure 1, is fitted at its one end with a thick disc-shaped target 105 formed of a good heat conductive material such as steel so as to form a part of the wall of an air-tight casing. This portion is shown in an enlarged scale in Figures 7 and 8, and as clearly illustrated, the target holder 105 is formed with an axial hole 106 along its axis and a radially extended hole 107 at the outer end. A metal target foil 108 is secured to the outer end face of the holder 105 and the open ends of the radial hole 107 are respectively closed in air-tight manner by cover plates 109 made of an X-ray permeable material such as beryllium. A cooling water pipe has a socket 110 into which the end of the tube 1 is fitted, and is formed with a channel 111 for cooling water to cool the outer surface of the foil 108.

Cooling water flows through the passage 111 as shown by arrow (a) in Figure 7. The electron current discharged from the filament 3 is accelerated through the elongate tube 1 to a voltage of several tens of thousands so as to form an electron beam *e* as shown by dotted lines in Figure 8. The beam *e* is focussed by coil 4 and the flux is passed through the axial hole 106 to form a focal point (P) on the surface of the target foil 108 whereby to emit X-rays from the foil 108. A portion of the X-rays is passed through the radial hole 107, which may be termed as an X-ray outlet hole, and utilised for any desired purpose such as for the ob-

servation of X-ray diffraction. Figure 9 shows a section of the focal point (P) on an enlarged scale, in which r designates the radius of the focal point (P) of the electron beam e, and B is a hemisphere with radius R from the centre, and the heat radiation E may be obtained as follows:

$$E=\frac{2\pi k\ (T_1-T_2)}{\frac{1}{r}-\frac{1}{R}} \qquad (7)$$

wherein, T_1 represents the temperature at the focal point (P), T_2 represents the temperature of the hemisphere B and (k) represents the thermal conductivity of the target foil 108. If the electron current is I and the velocity thereof is V, the power applied to the focal point (P) will be VI, therefore, the value VI should be maintained below the value E obtainable by Expression 7 given hereinabove. Assuming that all values T_1, T_2, (k) and (r) are constant, then it can be seen that the relationship between the radius R and the heat radiation E may be expressed as shown in Figure 10. Accordingly, it is clear that, given a constant temperature T_2, the radius R of the hemisphere B may be decreased as the permissible power VI of electron beams is increased. In the above described X-ray tube, a thin foil 108 is used as the target provided with a cooling water channel 111 so that a part of the target is cooled directly on its back surface, and a member 105 for holding the target foil 108 is formed with a good heat conductive material and provided with an axial hole 106 over which the foil 108 is directly secured. The remainder of the back area of the target is cooled by the cold surface of socket 110. When the temperature of the cooling water is T_2, the back of the foil 108 and the holder 105 is naturally maintained at the temperature T_2. The heat radiation E may be obtained by substituting the hemisphere radius R in Expression 7 by the thickness d of the foil 108. As shown in Figure 10, the smaller the value R, or the smaller the value of the foil thickness d, the heat radiation E increases, and thus the power VI to be applied to the target becomes higher due to the more intensive bombardment by the electron beam and consequently the stronger are the emitted X-rays. Since the target foil 108 is subjected to atmospheric pressure only at the portion exposed to the axial hole 106 and the radial hole 107, a very thin foil may be used as the target, and since the foil is simply secured to and held by the holder 105, the manufacture of the X-ray tube may be greatly facilitated.

The outer surface of the target foil may be coated with a heat resistive antioxidant layer. In case of a steel foil used as the target foil, one surface of the steel foil is preplated with platinum so that the plated platinum layer will serve as the antioxidant layer. When an aluminium foil is used as the target foil, one surface of the foil may be covered with an alumite layer for the same purpose.

In known X-ray tubes, when attempting to obtain strong X-rays by increasing the intensity of the bombardment of the electron beam against the target, the temperature of the target surface rises, and in an X-ray tube having the target contained in a hermetically sealed casing, the bombardment intensity is limited to keep the temperature below that at which the tube melts. It has been found that in such a known type of thin target X-ray tube, the target foil is gradually oxidised and deteriorates due to the temperature rise and finally cracks. Therefore, such X-ray tubes of the prior art have been found to have short lives due to oxidation of their target foils. The target foil may therefore be covered with a heat resistive antioxidant layer, whereby to avoid formation of cracks in the foil and thus increase the life of the X-ray tube. Since the target foil is protected from oxidation, the permissible working temperature may be elevated so as to increase the density of the electron beam and thereby increase the intensity of X-rays emitted. The antioxidant layer can be made very thin, therefore its absorption of X-rays may be minimised. However, in some applications, the tube may be arranged to emit secondary X-rays of suitable wave lengths from the antioxidant layer for a particular purpose.

WHAT WE CLAIM IS:—

1. An X-ray tube comprising an electron gun disposed adjacent one end of an elongate electron beam focussing tube, a thin target disposed at the other end of the tube and arranged to be bombarded by the accelerated electron beam, and protective means associated with the target to enhance the ability thereof to withstand deterioration, which would result from bombardment by said beam, including target supporting means, said target extending across the convergent end of a conical opening in said supporting means so that a portion of the target is exposed at said opening, and a cooling block having a channel for the passage of a cooling fluid therethrough at least at the side of said target remote from the beam, and arranged so that said side of the target has a surface area surrounding the exposed portion which is in mutual thermal exchange contact with a cooling surface or surfaces, said thermal exchange contact area extending over a major part of the cross section of said end of the tube.

2. A tube as claimed in Claim 1, wherein the whole of the area of said one side

of the target surrounding the exposed portion is in thermal exchange contact with a cooling surface consisting either of the block or partly of the block and partly of the cooling fluid.

3. A tube as claimed in Claim 1 or 2, wherein said protective means includes anti-oxidizing means to prevent the target from oxidizing.

4. A tube as claimed in Claim 1, 2 or 3, wherein said opening is provided in a block of good heat conducting material arranged between the target and the electron source and the beam passes through said opening.

5. A tube as claimed in Claim 1, wherein the target is arranged between a cooling block and the electron source, said block serving as support means for the target and containing the cooling channel and at least part of the X-rays emitted by the target pass through said opening.

6. A tube as claimed in Claim 1, 2, or 3, comprising a pair of corresponding blocks sandwiching the target therebetween said block each having an opening of coaxial conical form tapering towards each other, and two similar cooling channels are constituted by corresponding annular semi-circular grooves in the blocks juxtaposed to form a passage of toroidal shape, said passage being connected to means arranged to supply and remove a cooling fluid.

7. A tube as claimed in any of Claims 1 to 5, including window means between the target and the electron source for the passing of a part of the X-rays emitted by the target.

8. A tube as claimed in any of Claims 1, 2, 3, 4 and 6, wherein a cooling channel is positioned internally of said tube.

9. A tube as claimed in any of Claims 1 to 5, wherein a cooling channel is positioned at the side of the target remote from the electron beam.

10. A tube as claimed in any of Claims 1 to 9, wherein the target is a thin foil.

11. A tube as claimed in any one preceding claim, wherein the cooling block is of a metal having good thermal conductivity.

13. An apparatus for an X-ray tube constructed, arranged and adapted to operate substantially as hereinbefore described with reference to and as illustrated in Figures 1 to 3; Figures 4 and 5; or Figures 6 to 8 of the accompanying drawings.

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FIG.1.

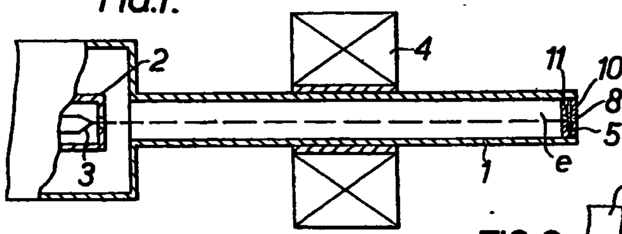

FIG.2.

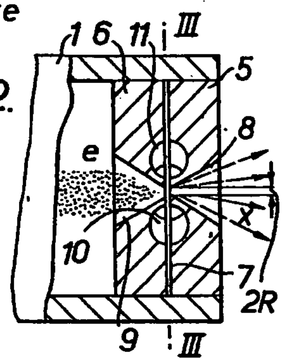

FIG.3.

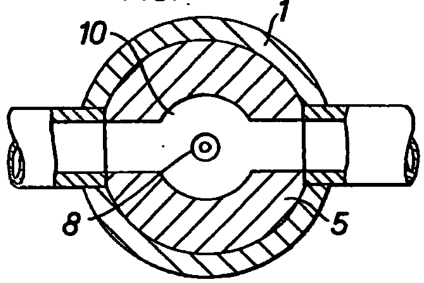

FIG.4.

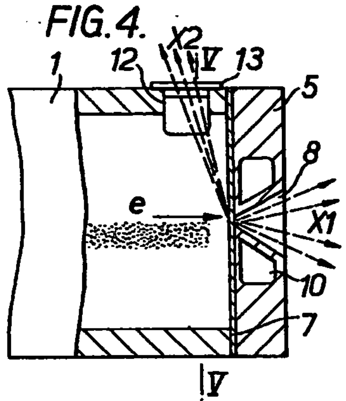

FIG.5.

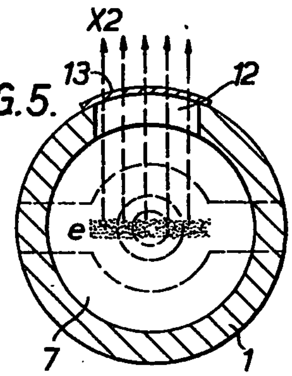

FIG.6.

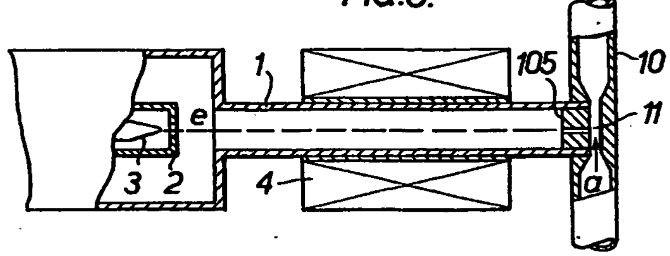

FIG.7.

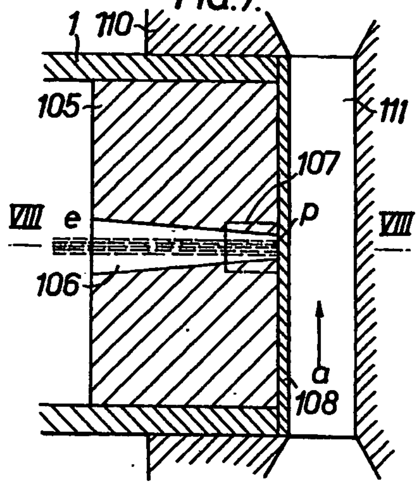

FIG.8.

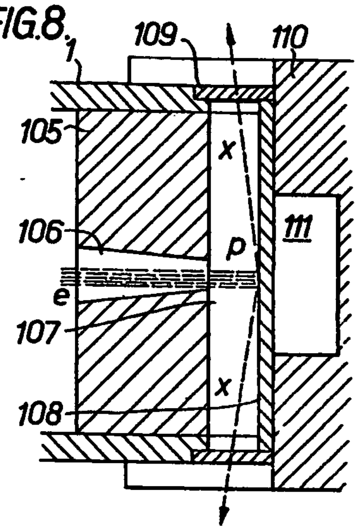

FIG.9.

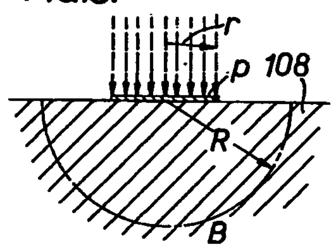

FIG.10.